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For a workshop at the Department of Mechanical and Aerospace Engineering, San Jose State Univ., San Jose, CA, 19 Aug 2011

14. ABSTRACT

This workshop focuses on plasma simulations on graphic processing units (GPU). A plasma is a gas in which an important fraction of the atoms is ionized, so that the electrons and ions are separately free. We need to keep track of Plasma's evolution, both in spatial and velocity space. Modeling methodologies include fluid methods and kinetic methods.

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Space Exploration Workshop
August 15-19, 2011

Plasma Simulations on the Graphic Processing Units (GPU)

Hai P. Le[*], *Jean-Luc Cambier*[†]

[*]Department of Mechanical and Aerospace Engineering
San José State University, CA 95192

[†]Air Force Research Laboratory
Edwards AFB, CA 93524

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Plasma

What is Plasma?

- A plasma is a gas in which an important fraction of the atoms is ionized, so that the electrons and ions are separately free.

How to model Plasma?

- We need to keep track of its evolution both in spatial and velocity space.

Modeling methodology:

- Fluid methods
- Kinetic methods

Driven Applications

- Electric Propulsion
- Laser-Plasma Interactions
- Hypersonic Re-entry
- Material Processing
- Astrophysics

Governing Equations

Starting from the Boltzmann equation of the distribution function of a multi-component plasma

$$\frac{\partial f_\alpha}{\partial t} + \vec{v} \cdot \vec{\nabla}_x f_\alpha + \vec{a} \cdot \vec{\nabla}_v f_\alpha = \sum_\beta C_{\alpha\beta}(f_\alpha) \tag{1}$$

Complete solution requires solving the convection equations for each plasma component in 6 dimensional coupled with the source terms on the RHS $\rightarrow$ highly computationally and memory intensive, model reduction required $\rightarrow$ fluid model

Fluid Description

Assumption

- Velocity distribution function is close to a Maxwellian distribution.

Approach

- Model the plasma using the fluid dynamical equations (Euler, Navier-Stokes)
- Thermochemical non-equilibrium environment can be characterized via multiple-temperature model
- Eletromagetic field effect can be modeled using the MHD approximation.

Fluid Equations

Two-temperature plasma ($T_h - T_e$)

$$\frac{\partial Q}{\partial t} + \frac{1}{V}\oint_S F_n dS = \dot{\Omega} \tag{2}$$

$$Q = \begin{pmatrix} \rho_s \\ \rho u \\ \rho v \\ \rho w \\ E \\ S_e \end{pmatrix}; F_n = \begin{pmatrix} \rho_s U_n \\ P n_x + \rho u U_n \\ P n_y + \rho v U_n \\ P n_z + \rho w U_n \\ U_n H \\ U_n S_e \end{pmatrix}$$

$$\dot{\Omega} = \dot{\Omega}_{\mathrm{CR}} + \dot{\Omega}_{\mathrm{Chem}} + \dot{\Omega}_{\mathrm{cond}} + \dots \tag{3}$$

Solution method:

- Finite Volume method for hyperbolic conservation laws
- Source terms are solved by using operator splitting technique

Kinetic Description

Assumption

- High temperature
- Low density

Approach

- Treat the plasma as a set of pseudo-particles moving in the electromagnetic field computed on a grid (Particle In Cell).
- The plasma is then modeled by intergrating the equation of motion (Lorentz equations) for each particle inside the field. The field is also updated by solving the Maxwell equations.
- Ionization can be modeled by particle collision (e.g. Monte-Carlo collision)

Particle-in-Cell Method

Particle equation of motion

$$m\frac{d\vec{v}}{dt} = q(\vec{\mathcal{E}} + \vec{v} \times \vec{\mathcal{B}}) \tag{4}$$

Field Equation

- Electrostatic: Poisson equation

$$\vec{\nabla}^2\phi = \frac{e}{\varepsilon_0}(Z_i n_i - n_e) \tag{5}$$

  where $\vec{\mathcal{E}}_n = -\nabla_n\phi$

- Electromagnetic: Maxwell equations

Current Focus

Current Focus

- Basic framework for Fluid (CFD) and Particle (PIC) simulations on GPU
  - Fluid: CFD solver with reaction kinetics
  - Particle: Electrostatic PIC

Graphic Processing Unit

What is GPU?

- Graphic processing units containing a massive amount of processing cores
- Designed specifically for graphic rendering which is a highly parallel process

Why GPU?

- GPU is faster than CPU on SIMD execution model
- GPU is now very easy to program
- GPU is much cheaper than CPU

GPU versus CPU

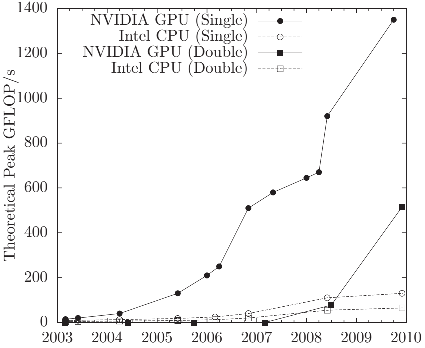


Figure: Single and double precision floating point operation capability of GPU and CPU from 2003-2010

GPU Programming

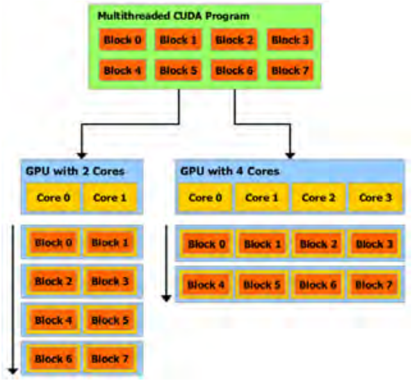
Programming languages for GPU: CUDA, OpenCL, DirectCompute, BrookGPU, ...

CUDA is the most mature programing environment for GPU.

- similar to C/C++
- support OO features
- easy to debug

GPU Programming Model

- Based on *grid* and *thread blocks*
- Execution instruction called *kernel*



GPU Implementation

CFD:

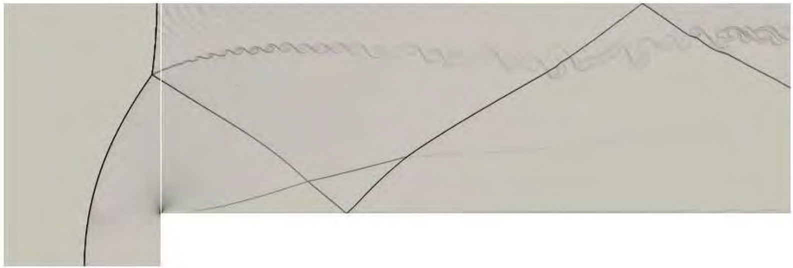
- Map the computational domain with CUDA grid
- All the computational cells can be processed in parallel

PIC:

- Associate particles with threads and have each thread integrate the equation of motion.
- Associate field quantities of the cells with threads and have each thread update the field value of the cell.

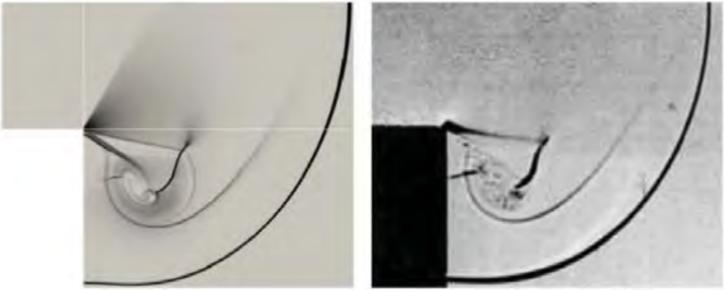
CFD

Forward step - Mach 3 flow over a step



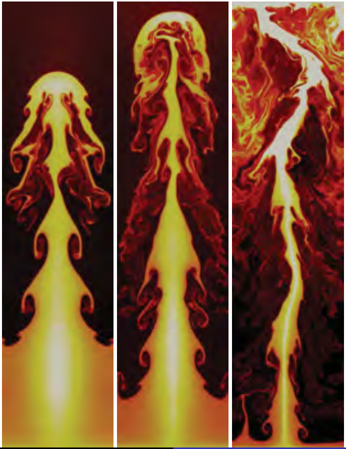
CFD

Backward step - Mach 2.4 shock diffraction



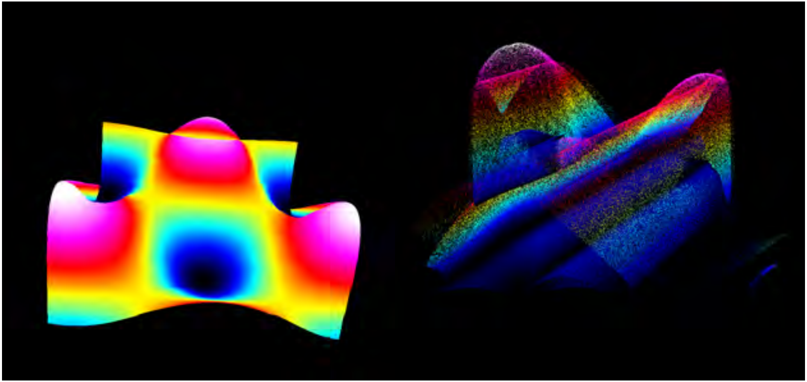
CFD

Rayleigh-Taylor Instability - Acceleration of a heavy fluid to a lighter fluid



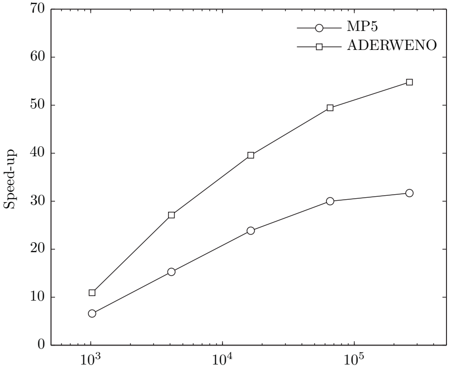
PIC

PIC Demo



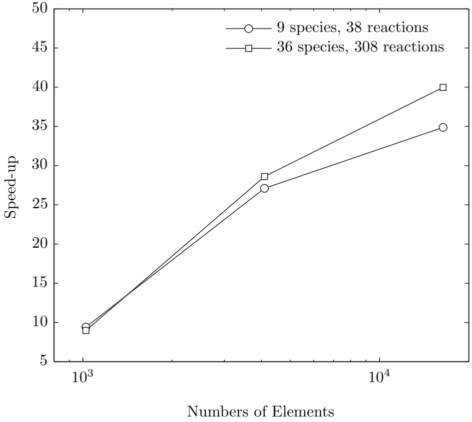
Performance

Without chemical kinetics



Performance

With chemical kinetics



Conclusion and Future Works

Accomplishment:

- Basic CFD framework for fluid simulation and PIC framework for electrostatic field on the GPU
- Performance obtained in both cases are very promising

Future Works:

- Plasma ionization kinetics (CR model) for fluid modeling.
- Monte-Carlo collision for PIC (PIC-MCC)
- Multi-fluid and hybrid modeling
    - Model each component of the plasma by different methods

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